FINAL REPORT

N00024-90-C-4538 As Amended

SBIR TOPIC N88-94

EVALUATION OF LAB TESTS

OF THE

INTERNAL REFORMATION OF

DESULFURIZED DIESEL FUEL

IN AN MCFC TEST STACK

March 1993

Prepared by

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PROJECT SUMMARY

Purpose of the Work

To demonstrate the internal reformation of diesel type fuel in a representative high temperature molten carbonate or direct fuel cell (DFC) stack and to evaluate the results of the demonstration after at least 400 hours of operation.

Description of the Work Carried Out

Starting with the known capability of DFC stacks to internally reform natural gas (CH_4), the fuel vaporization and judicious breaking of the carbon bond in the more complex diesel type fuel molecule (represented typically as C_7H_{14}) was addressed. Free carbon could potentially load up the reformer passages and is thus to be avoided. Following careful testing of numerous sub scale vaporization, fuel conditioning and reforming techniques, the most appropriate thermochemical means was derived by the AEL test subcontractor Energy Research Corporation (ERC). It consists of a combined fuel vaporizer and adiabatic fuel conditioner column which, in effect, creates synthesized CH_4 molecules from the heavier hydrocarbon and then steam reforms the synthesis gas in the plate type reformer within the stack using the heat from the fuel cell stack.

The demonstration was successfully carried out in August 1992 for 400 hours under the Navy contract plus an additional 200 hours under a contract from the Electric Power Research Institute (EPRI). The equipment was then to be dismantled and the internal characteristics of the reformer and the DFC test stack analyzed and evaluated to determine whether any life-limiting phenomena had occurred.

Findings and Results

The small scale system has worked. The fuel was vaporized, reformed and electrochemically reacted to produce DC electricity and fresh water for the contracted 600 hour test. No degradation of the performance was noted during the 600 hours. The dismantled reformer plate and stack cells showed no carbon buildup.

Potential Application of the Effort

The successful demonstration of the internal reformation of diesel type fuel in a DFC stack at a small laboratory scale now defines the need to scale up the test to at least a 10 kW power level using a stack of a commercial cross section of at least 2 ft x 2 ft. This has been proposed to the Navy, using an existing DFC stack owned by the Department of Energy (DOE) and a test setup owned by EPRI, both located at ERC in Danbury, CN. The Navy has agreed to supply, as government furnished material (GFM), an amount of desulfurized diesel fuel sufficient for such a 400 hour test.

Fuel cell propulsion for ships will be very energy conversion efficient, will produce clean, quiet power with virtually no maintenance, will produce potable water and high quality waste heat. They will be rapidly changed-out because of the one-sided-fit modular approach used in the design.

SIGN OFF FOR THE SBIR TOPIC N88-94 PHASE II FINAL REPORT

Contract N00024-90-C-4538

Contractor's Principal Investigator Sign Off On Report Contents

1. Pursuant to DD1423 A003 Technical Data Rights Claimed:

   No technical data rights are claimed under this laboratory test
   and evaluation contract.

2. Pursuant to DD1423 A004 Computer Software Product:

   No software products were developed under this laboratory test and
   evaluation contract.

3. Pursuant to DD1423 A006 System/Segment Specification:

   No hardware system was to be delivered under the laboratory test
   and evaluation contract so no specification is applicable.

4. Pursuant to DD1423 A010 and A011 Product Drawings and Associated Lists:

   No hardware product was to be delivered under this laboratory
   test and evaluation contract.

5. Pursuant to DD1423 A012 Report of Inventions and Disclosure:

   Two inventions/patentable disclosures were made by the AEL special
   test subcontractor ERC under this laboratory test and evaluation
   contract. Executed Form 882's have been filed with NAVSEA.

William H. Kumm   March 30, 1993

William H. Kumm   PI and   President of Arctic Energies Ltd.(AEL)   Date

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Unannounced	☐	
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1. INTRODUCTION

1.1 Summary

The purpose of the contracted work was to demonstrate the internal reformation of diesel type fuel in a representative high temperature molten carbonate or direct fuel cell (DFC) stack and to evaluate the results of the demonstration after at least 400 hours of operation.

Starting with the known capability of DFC stacks to internally reform natural gas (CH_4), the fuel vaporization and judicious breaking of the carbon bond in the more complex diesel type fuel molecule (represented typically as C_7H_{14}) was addressed. Free carbon could potentially load up the reformer passages and is thus to be avoided. Following careful testing of numerous sub scale vaporization, fuel conditioning and reforming techniques, the most appropriate thermochemical means was derived by the AEL test subcontractor Energy Research Corporation (ERC). It consists of a combined fuel vaporizer and adiabatic fuel conditioner column which, in effect, creates synthesized CH_4 molecules from the heavier hydrocarbon and then steam reforms the synthesis gas in the plate type reformer within the stack using the heat from the fuel cell stack.

The demonstration was successfully carried out in August 1992 for 400 hours under the Navy contract plus an additional 200 hours under a contract from the Electric Power Research Institute (EPRI). The equipment was then to be dismantled and the internal characteristics of the reformer and the DFC test stack analyzed and evaluated to determine whether any life-limiting phenomena had occurred. The small scale system test work has been successful. The fuel was vaporized, reformed and electrochemically reacted to produce DC electricity and fresh water for the contracted 600 hour test. No degradation of the performance was noted during the 600 hours. The dismantled reformer plate and stack cells showed no carbon buildup.

The EPRI was pleased with the results of the work and we trust the Navy is also. The SBIR Program has been successful in Phases I and II and AEL looks forward to Phase III and beyond.

1.2 Conclusion

The successful demonstration of the internal reformation of diesel type fuel in a DFC stack at a small laboratory scale now defines the need to scale up the test to at least a 10 kW power level using a stack of a commercial cross section of at least 2 ft x 2 ft. This has been proposed to the Navy, using an existing DFC stack owned by the Department of Energy (DOE) and a test setup owned by EPRI, both located at ERC in Danbury, CN. The Navy has agreed to supply, as government furnished material (GFM), an amount of desulfurized diesel fuel sufficient for such as 400 hour test.

Once the 10 kW power level testing has been completed and a preliminary design task to define the physical configuration of roughly 6 ft tall "half height" 60 kW DFC stack module is completed, a full scale naval power plant can be designed. The DFC technology from which this design is derived is that of the on-land outdoor electric utility configuration. These natural gas fueled utility units are currently rated at 120 kW in a 2 ft x 3 ft cross section 12 ft tall stack. No utility funded effort is currently underway to reduce weight or volume. All of the utility-oriented effort is devoted to reducing price per kW installed and to reducing the fuel rate or heat rate.

The naval or maritime type 60 kW stacks will have a one-sided-fit with all manifolds and service connections brought out through the bottom of the replaceable modules. Fuel cell propelled small ships can then be designed and built using these modules based on DFC stacks with a 2 ft x 3 ft (6 ft^2) cross sectional area. Subsequent higher power systems will be based on 16 ft^2 (4 ft x 4 ft) stack cells with a correspondingly higher power rating of the order of 160 kW per 6 ft tall modules.

The above description of a commercialization path assumes no parallel funded effort to reduce DFC weight and volume per kW. Adequate design and manufacturing expenditures on that performance improvement path will then permit reductions of the order of 30% in each of these two characteristics of DFCs.

Cooperation between the Navy and the civil sector agencies which operate ships, as well as with the private sector ship owners, will accelerate the introduction of fuel cell propulsion for ships of all kinds.

2. DETAILED DESCRIPTION OF WORK

2.1 Scope

For a number of non-utility Direct Fuel Cell (DFC) applications, liquid fuels rather than natural gas are the fuels of interest. For naval applications, the fuel cell power plants need to be operated with diesel fuel. While much effort has been expended in the demonstration of efficiency and endurance of DFCs powered by natural gas, operating experience with diesel fuel is lacking. A project was therefore carried out under the sponsorship of NAVSEA to build and operate a DFC system for 400-hours on sulfur-free diesel or equivalent fuel in order to demonstrate the feasibility of running DFC power plants with diesel-type and other logistic liquid fuels. A further 200-hours of testing were sponsored by the Electric Power Research Corporation (EPRI). The demonstration was performed successfully by Energy Research Corporation (ERC) under subcontract to Arctic Energies Ltd. (AEL). The two companies have been collaborating toward development of applications for the DFC technology based on logistic liquid fuels in the defense and remote polar power areas. This report describes the test article and summarizes the result of the liquid fuel DFC system demonstration test.
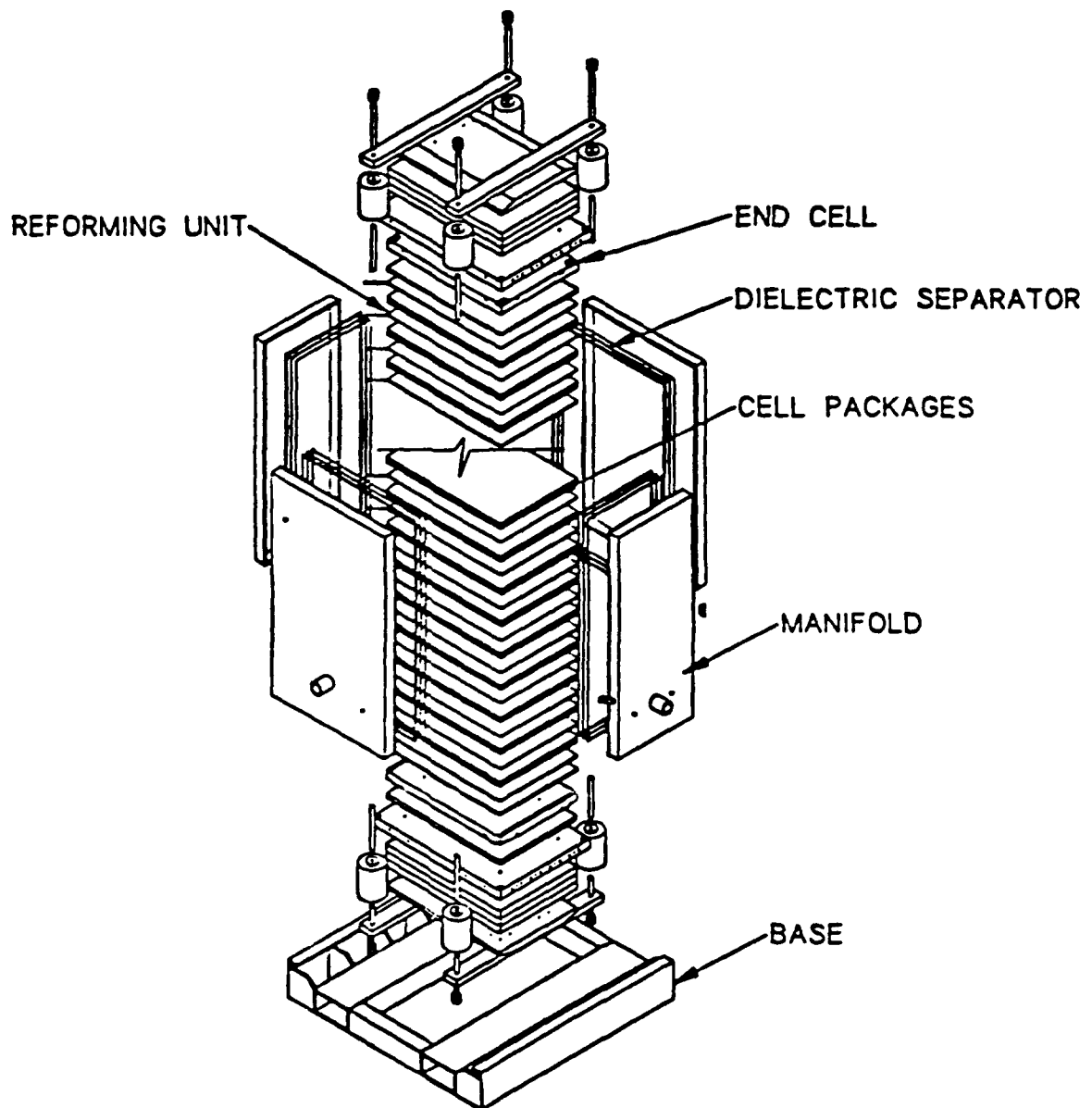
2.2 Technical Background

Fuel cells convert chemical energy of fuel directly into electricity without any intermediate conversion to heat and mechanical energy. Direct carbonate fuel cells (DFCs) are capable of reforming hydrocarbon fuels internally without the use of external reformers. Therefore, they are more efficient and simpler than other types of fuel cells. Direct fuel cells are currently under development for use with natural gas fuel as well as coal derived gaseous fuels. This gas fueled work is sponsored mainly by the Department of Energy, the Electric Power Research Institute, and a group of municipal and private utility companies.

ERC's carbonate fuel cell stacks have been developed for utility power generation and incorporate internal reforming plate units which allow direct conversion of natural gas into hydrogen which is used in the fuel cell anodes for electrochemical power generation. Reforming plates are incorporated in the fuel cell stack and supplied with the gaseous fuel from a common header as illustrated in Figure 1. Internal reforming reduces equipment complexity by eliminating the need for external reforming equipment, increases system efficiency by utilizing the stack waste heat for reforming, and reduces the cooling requirement for the stack.

Figure 2 illustrates the chemical reactions which occur in the direct fuel cell (DFC) stack. The main reaction in the stack internal reforming units is conversion of methane to hydrogen. Hydrogen is then consumed in the power producing reaction in the electrochemical cells. The roughly 5% hydrogen remaining in the anode tailgas is combusted with excess air to provide oxygen and carbon dioxide.

REFORMING UNIT

END CELL

DIELECTRIC SEPARATOR

CELL PACKAGES

MANIFOLD

BASE

FIGURE 1 DFC STACK ASSEMBLY

CARBONACEOUS FUEL → $CH_4 + H_2O \rightleftharpoons CO + 3H_2$

$H_2 + CO_3^= \rightleftharpoons H_2O + CO_2 + 2\bar{e}$

$\uparrow CO_3^=$

AIR + CO$_2$ → $2\bar{e} + CO_2 + 1/2\,O_2 \rightleftharpoons CO_3^=$
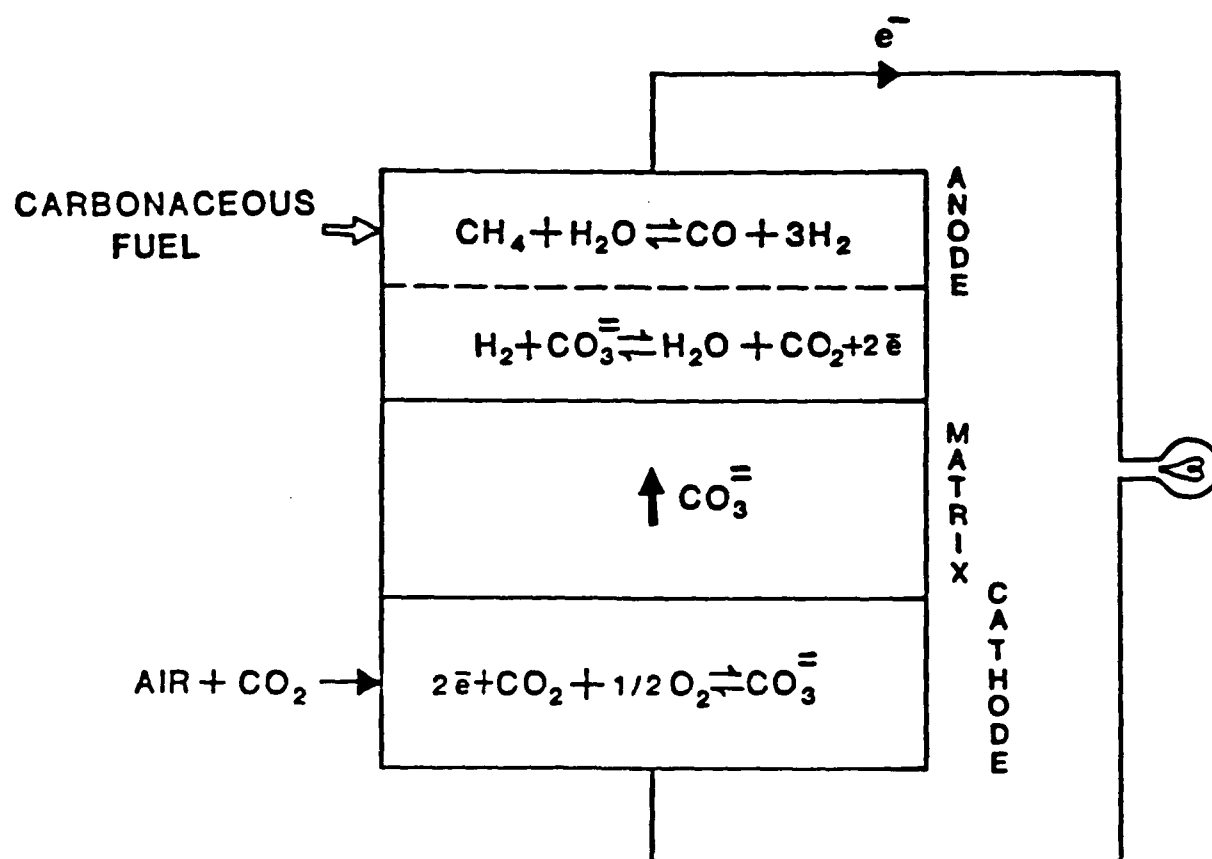
e^-

ANODE

MATRIX

CATHODE

FIGURE 2 DIRECT FUEL CELL OPERATING PRINCIPLE

The steam for reforming is raised by exchanging heat with the cathode exhaust gas. A simplified flow diagram illustrating the system concept of a methane (natural gas) fired DFC power source is shown in Figure 3.

For naval applications, liquid fuels, and diesel fuel in particular, are of interest. Liquid fuels require processing conditions which are different than those used with natural gas fired DFC systems. These fuels have a strong propensity for carbon formation (coking) at the conditions existing in the DFC reforming units.

The DFC stack reforming plate units (RUs) have been designed for achieving high efficiency of conversion of methane to hydrogen. For operation with higher molecular weight hydrocarbons including diesel, pre-reforming to methane is the best approach for assuring efficient operation on liquid fuel with a simple DFC plant design. The resulting DFC thus has a multi-fuel capability.

The concept of fuel preconversion has been used in various syngas plant designs where liquid fuels such as naphtha or LPG are processed. This approach improves feedstock flexibility and allows operation of the primary reformer at low steam to carbon ratios. The preconverter (PC) is an adiabatic catalytic reaction operating typically at between 400° C and 500° C. The PC converts the hydrocarbon feed to a mixture of methane, hydrogen, and carbon oxides in the presence of steam. Both the endothermic reforming process and the exothermic methanation reactions take place in the adiabatic reactor. Heat of reaction needed for the reforming step to proceed is provided by sensible heat from the feed stream mixture flowing to the reactor. Because of the low temperature, relatively low steam to carbon ratios may be employed. The advantages of adiabatic operation are, of course, the preservation of DFC system's simplicity and high thermal efficiency.

2.3 Test Article Description

2.3.1 Fuel

The fuel specified for this demonstration was a narrow-cut aliphatic solvent supplied by the Exxon Corporation. The solvent is marketed worldwide as EXXSOL D110 by the manufacturer and is used in a broad range of industrial applications. Selected chemical and physical properties specified by the manufacturer for this solvent are seen in Table 1 along with actual values measured for the material lot used for this study. Selected properties for diesel fuel are shown for comparison. The primary reason for using EXXSOL D110 is its similarity to diesel fuel and the low sulfur content which makes it suitable for evaluation as an internally reforming carbonate fuel cell reactant without further processing for sulfur removal.

FIGURE 3 DFC SYSTEM CONCEPT

7
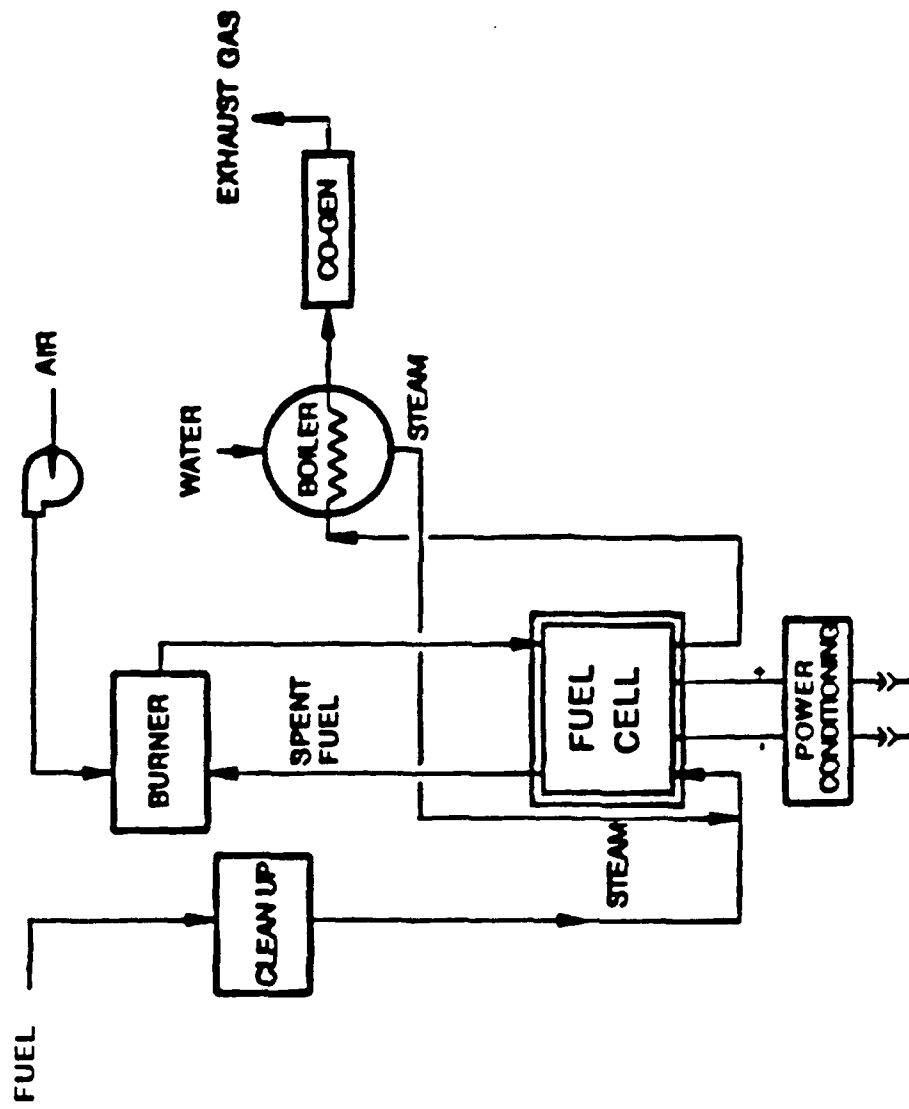
TABLE 1 PROPERTIES OF EXXSOL D110

	Specification	Measured*	Test Method	DIESEL FUEL
Composition, Mass %				
Aromatics	0.6	0.374	Gas Chromatography	
Naphthenes	47			
Paraffins	52			
Volatility				
Flash point, PM °C (°F)	113 (235)	119 (246)	ASTM D 93	
Vapor pressure, psia @ 100°F	0.015		ASTM D 2979	
Distillation, °C (°F)			ASTM D 86	
IBP	243 (469)	252 (485)		163 (325)
10%	248 (478)			
50%	250 (482)			
90%	256 (492)			
Dry point	259 (499)	267 (513)		343 (650)
Auto-ignition temperature, °C (°F)	211 (412)		ASTM E 659	254 (490)
General				
Color, Saybolt	+30	+30	ASTM D 156	
Specific gravity @ 15.6°/15.6°D	0.807	0.8102	ASTM D 287	0.85
kg/m³ (lb/gal)	805 (6.72)		ASTM D 1250	848 (7.08)
Sulfur, ppm (weight)	3	1	Microcoulometer	5,000
Viscosity, cSt @ 20°C	1.445		ASTM D 1218	

A carbon-hydrogen analysis for the test fuel showed 86.3% carbon and 14.1% hydrogen, which indicates an empirical formula of $CH_{1.95}$. By comparison, the heaviest diesel fuel, DF-2 has the empirical formula $CH_{1.7}$. EXXSOL D110 may be expected to have fuel processing requirements somewhere between those of diesel oil and naphtha, which has an empirical formula $CH_{2.2}$.

2.3.2 Fuel Cell Stack

The carbonate fuel cell stack used for the 400-hour demonstration consisted of 5 cells each measuring 7 in. x 7 in. overall. The active electrode area of the cells was 0.25 ft^2. The stack was assembled with endplate heaters and was supported in a pneumatic compression rig.

2.3.3 Reforming Unit (RU) Plate

The reforming unit (RU) plate was scaled to reform fuel for the 5-cell stack at nominal operating conditions of 150 mA/cm^2 (35A), and had overall dimensions of 7 in. x 7 in. The standard nickel reforming catalyst used in all of ERC's direct fuel cell stacks was employed.

The internal reforming unit was assembled unit was assembled in a separate support rig which was equipped with separate heaters and temperature regulator. This assembly arrangement was chosen over a single assembly comprising the fuel cell stack and the reforming plate as a precaution against the loss of the fuel cell stack in case of a test facility upset resulting in damage to the reforming unit.

2.3.4 Vaporizer/Preconverter

Preliminary testing for ability to directly reform the EXXSOL D110 fuel in the reforming unit produced heavy carbon deposition. Increasing the ratio of steam to carbon ratio to values as high as S/C = 10 did not entirely eliminate carbon formation. An auxiliary fuel converter reactor was therefore constructed and installed ahead of the reforming unit. This reactor operates at 400-450° C and converts the higher hydrocarbons to methane, hydrogen and carbon dioxide. The principal reactions in the preconverter are endothermic reforming to CO and H_2 followed by exothermic methanation to CH_4 and CO_2. A two-pass reactor tube design was utilized as shown in Figure 4 to enhance heat transfer within the catalyst bed. Because of the small scale of the equipment, clamshell heaters were used to maintain the desired reactor bed temperature of 400-450°.
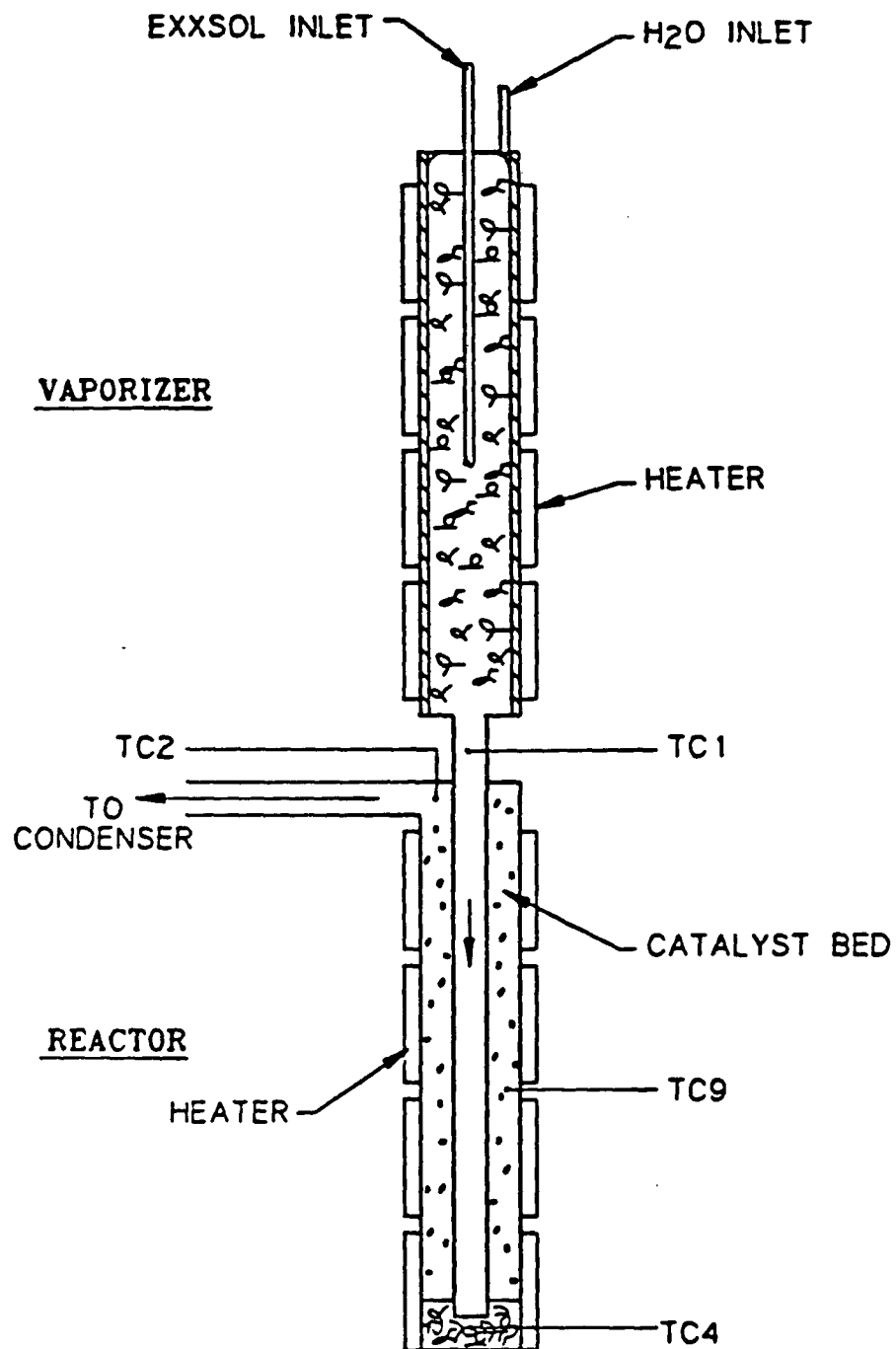
FIGURE 4 VAPORIZER AND PRECONVERTER

The preconverter column employed concentric tubes. The outer tube had an OD of 2 inches and the inner tube had an OD of 3/4 inches. The wall thickness of both tubes was 0.035 inches. The nickel catalyst column of 30 inches, of which 27 inches were packed with catalyst. The rest of the column (ends) contained packing material. The catalyst weight was approximately 1.2 kg.

The vaporizer had an O.D. of 2 inches and a wall thickness of 0.035 inches. It was filled with stainless steel wool for a packed height of about 26 inches. Water entered at the top while EXXSOL D110 liquid inlet was at roughly midpoint of the vertical vaporizer column. External clamshell heaters were used to supply heat.

2.4 System Arrangement

The arrangement of the principal components used for the 400-hour demonstration run is shown in Figure 5. The preconverter was built as an integral unit with the vaporizer. Fuel and water were pumped to the top of the downflow vaporizer column. The vaporized fuel and mixture passed through the preconverter reactor to the reforming unit and the anode of the fuel cell stack. Figure 6 shows a photograph of the equipment setup. The vaporizer/preconverter is larger than required for the small scale Navy and EPRI test conducted. It was built to supply reforming plates for a 2 kW stack to be tested later.

The overall arrangement of the test facility is shown schematically in Figure 7. The stack was set up to allow operation with both hydrogen fuel and EXXSOL D110, the test fuel. Traditional anode and cathode gas compositions were used during system start and stack performance characterization testing. A standby gas system and auxiliary power source were installed to provide orderly system shutdown in case of test equipment failure or loss of mains power.

2.5 Operating Procedure

2.5.1 Fuel Cell Stack Conditioning

The fuel cell stack was operated on simulated reformed gas (SRG) fuel for a period of about 900 hours before the testing with EXXSOL D110 commenced. The SRG fuel composition during this period of stack operation was:

H_2	73.0%
CO	18.0%
H_2O	9.0%

FIGURE 5

DFC DEMONSTRATION TEST ARRANGEMENT

PRECONVERTER

WATER

FUEL

VAPORIZER

PRE-
CONVERTER

750-800°F

PRECONVERTED FUEL

(CH₄, CO₂, H₂)

REFORMING
UNIT

1200-1250°F

REFORMATE

(H₂, CO₂)

CELL STACK

EXHAUST

1200-1250°F
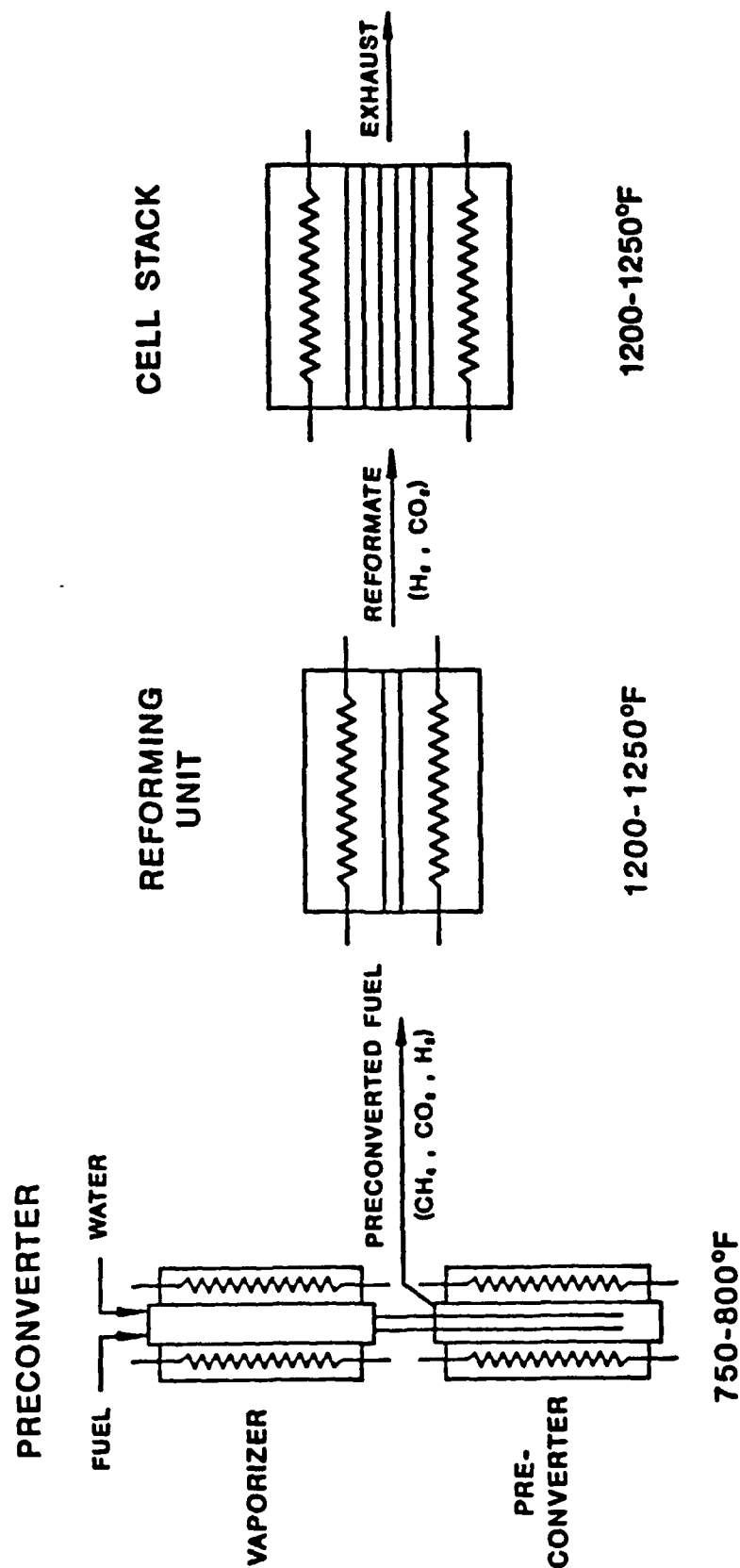
SEPARATE PROCESS UNITS ALLOW
INDEPENDENT CONTROL AND MONITORING

SD1211

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FIGURE 6 EQUIPMENT SETUP

VAPORIZER/PRECONVERTER

REFORMING UNIT

5 CELL STACK
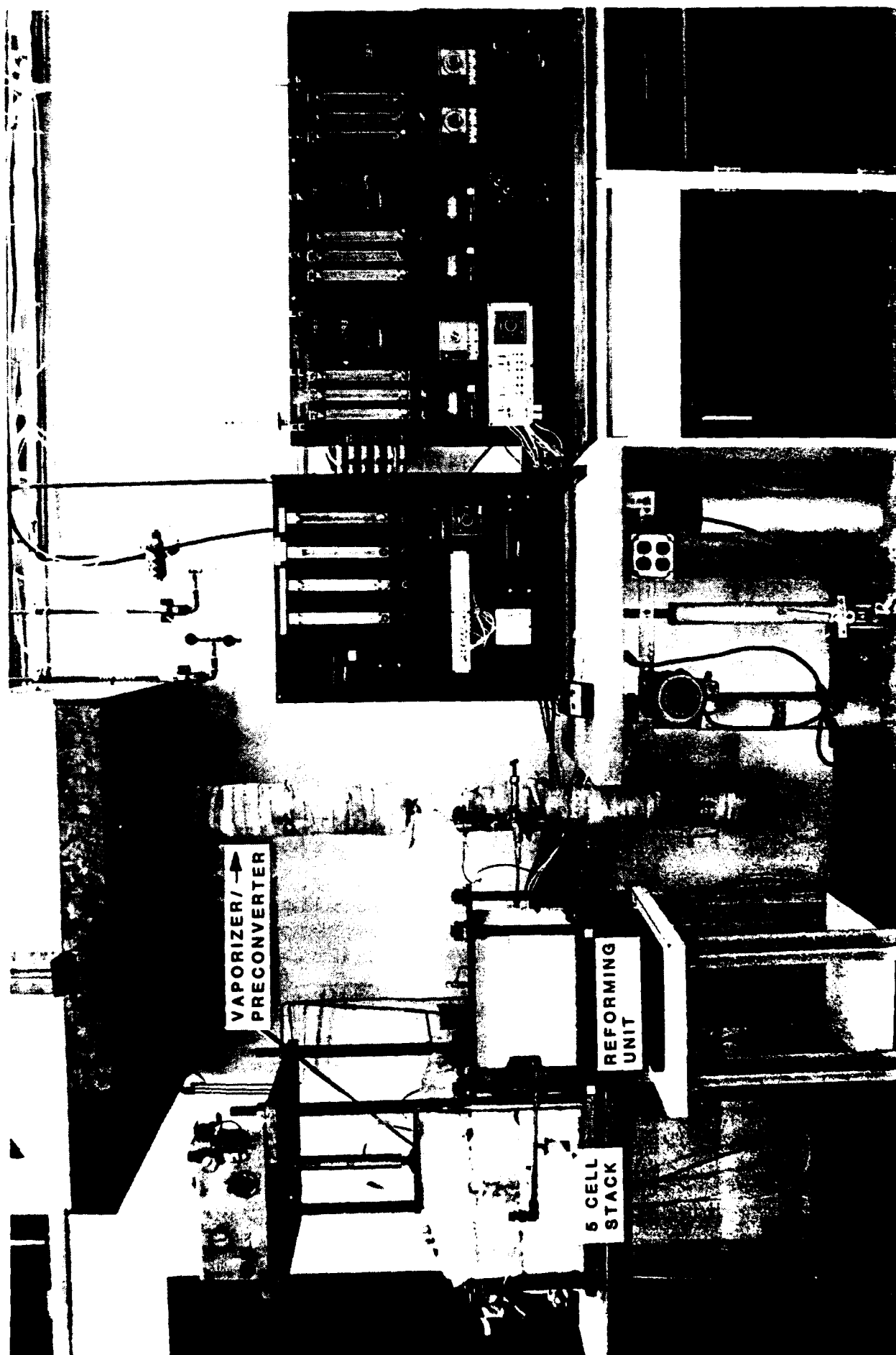
FIGURE 7 SCHEMATIC OF TEST FACILITY ARRANGEMENT

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The stack cathode gas used was based on simulated SRG burner recycle stream and had the composition:

$$O_2 \quad 9.7\%$$
$$CO2 \quad 13.8\%$$
$$N_2 \quad 76.5\%$$

The initial stack operating period served to stabilize stack output voltage at the nominal stack current of 35 amperes (150 amperes/square foot) and to establish any rate of stack voltage change with time on SRG fuel. This established the baseline stack voltage for evaluation of the effect of EXXSOL D110 fuel on output voltage.
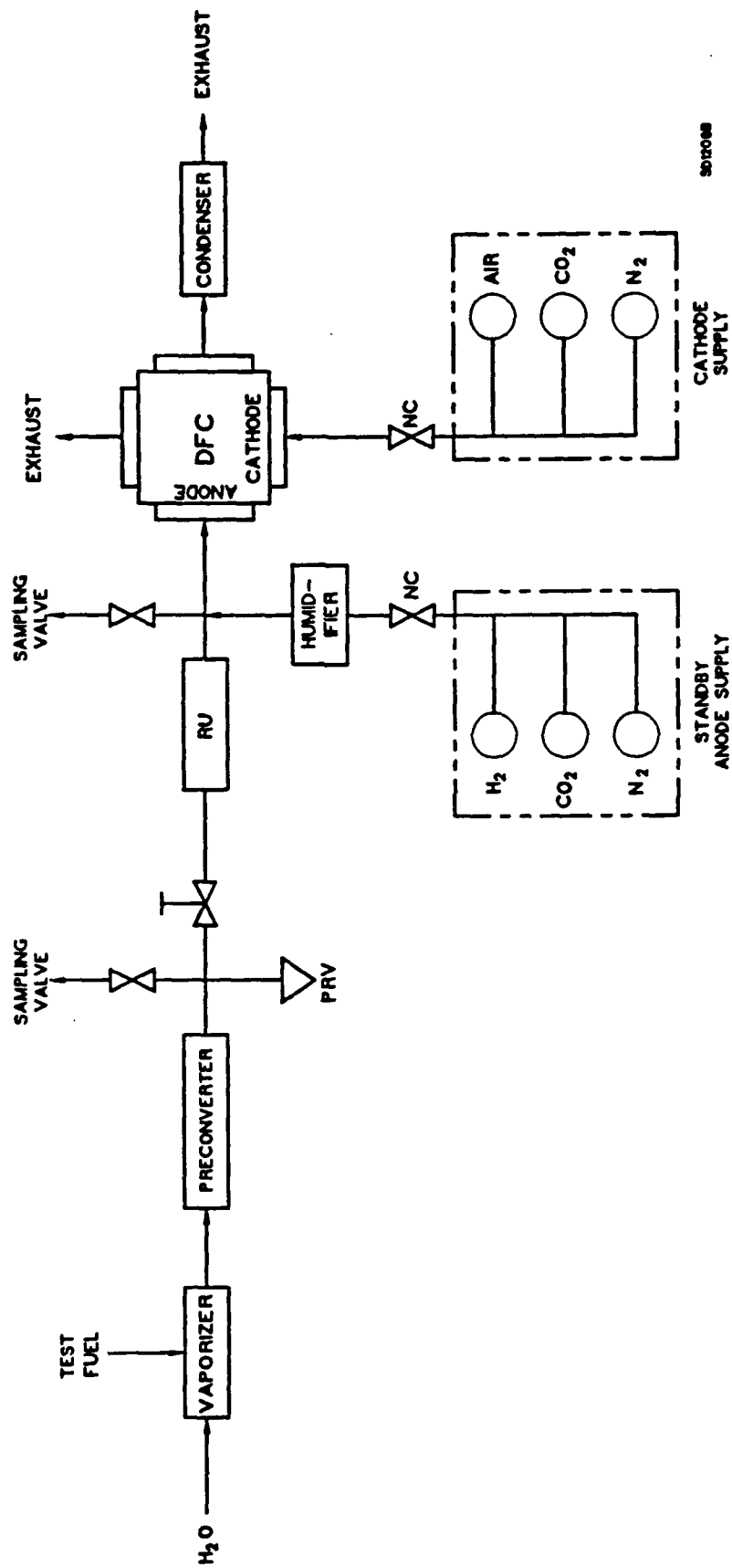
2.5.2   Preconverter Conditioning

The preconverter was operated for a short time (less than 100 hours) to establish control parameters for steady state operation at the conditions to be used during the test run. Performance stability was demonstrated by periodically verifying product gas composition stability and by monitoring internal reactor temperatures.

2.5.3   System Operation

The demonstration run with EXXSOL D110 fuel commenced directly after operation of the stack with SRG without system shutdown. Following a brief period (5 minutes) of operation with both SRG and EXXSOL D110 flowing, the SRG flow was shut off. Operation of the system than continued on a 24 hour/day basis with EXXSOL D110 fuel for a total of 630 hours. Simulated reformer gas was introduced into the anode stream and the liquid fuel and water flow to the system were turned off. The test was interrupted once for about 100 hours to replace a defective temperature controller. During this 100 hour period the stack continued to operate with SRG fuel.

The temperature of key test equipment and of the process streams were monitored continuously and recorded periodically on data sheets. Appendix 1 shows an example of the recorded data. In addition to the manually recorded data, a continuous record was obtained of key process parameters by the use of strip chart recorders. The continuously recorded parameters were stack voltage, stack current and stack temperature.

2.6 Results

For the duration of the entire test run, all monitored parameters remained within normal operating range. The reformate composition exiting the RU plate also

FIGURE 8 NAVSEA/EPRI DFC DEMONSTRATION
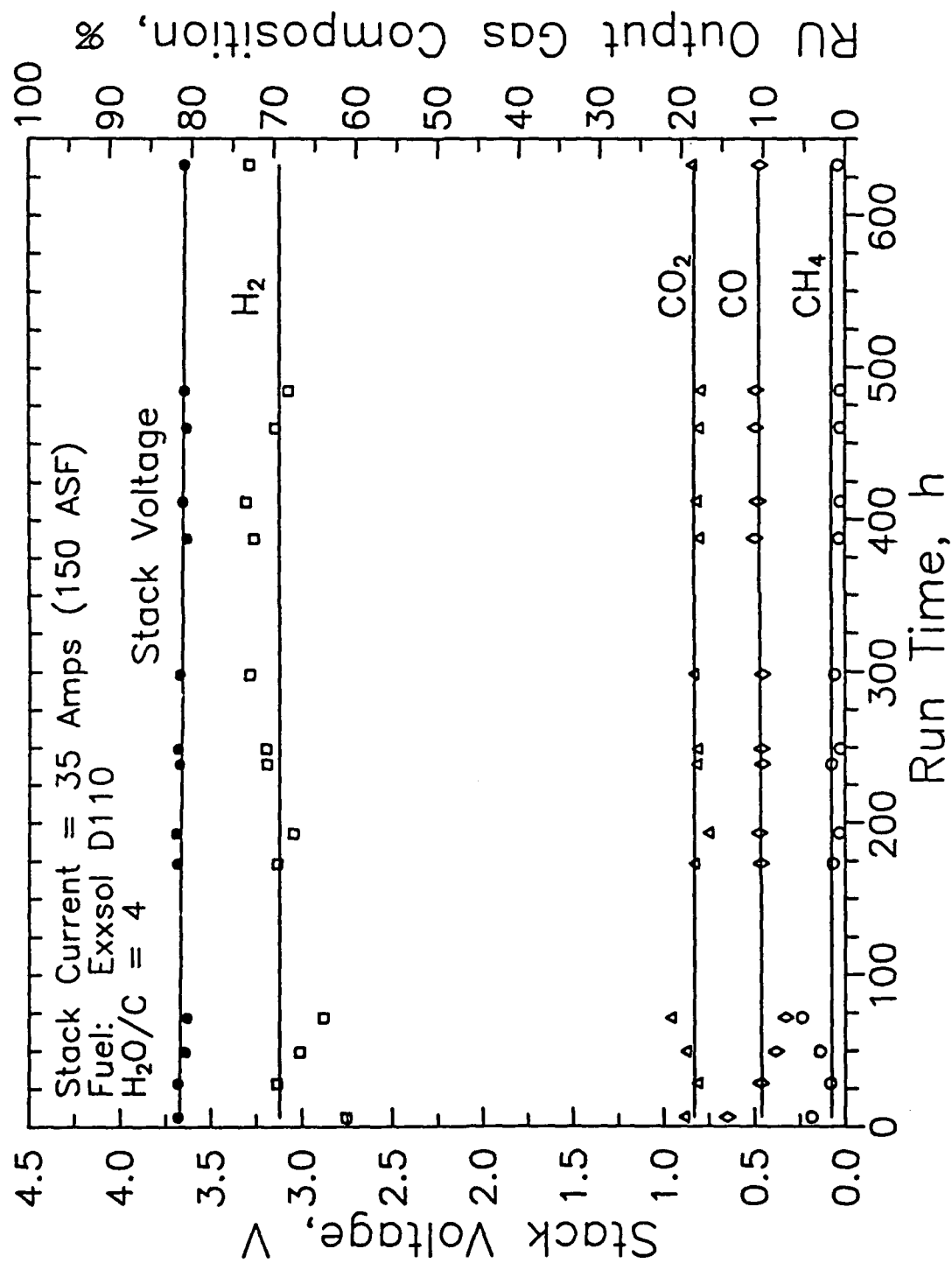
FIGURE 9 STACK PERFORMANCE WITH SRG (H₂) AND EXXSOL D110 FUEL

35 A (150 ASF)
650°C

SRG

Exxsol D110
670 hours

SRG

Stack Voltage, V
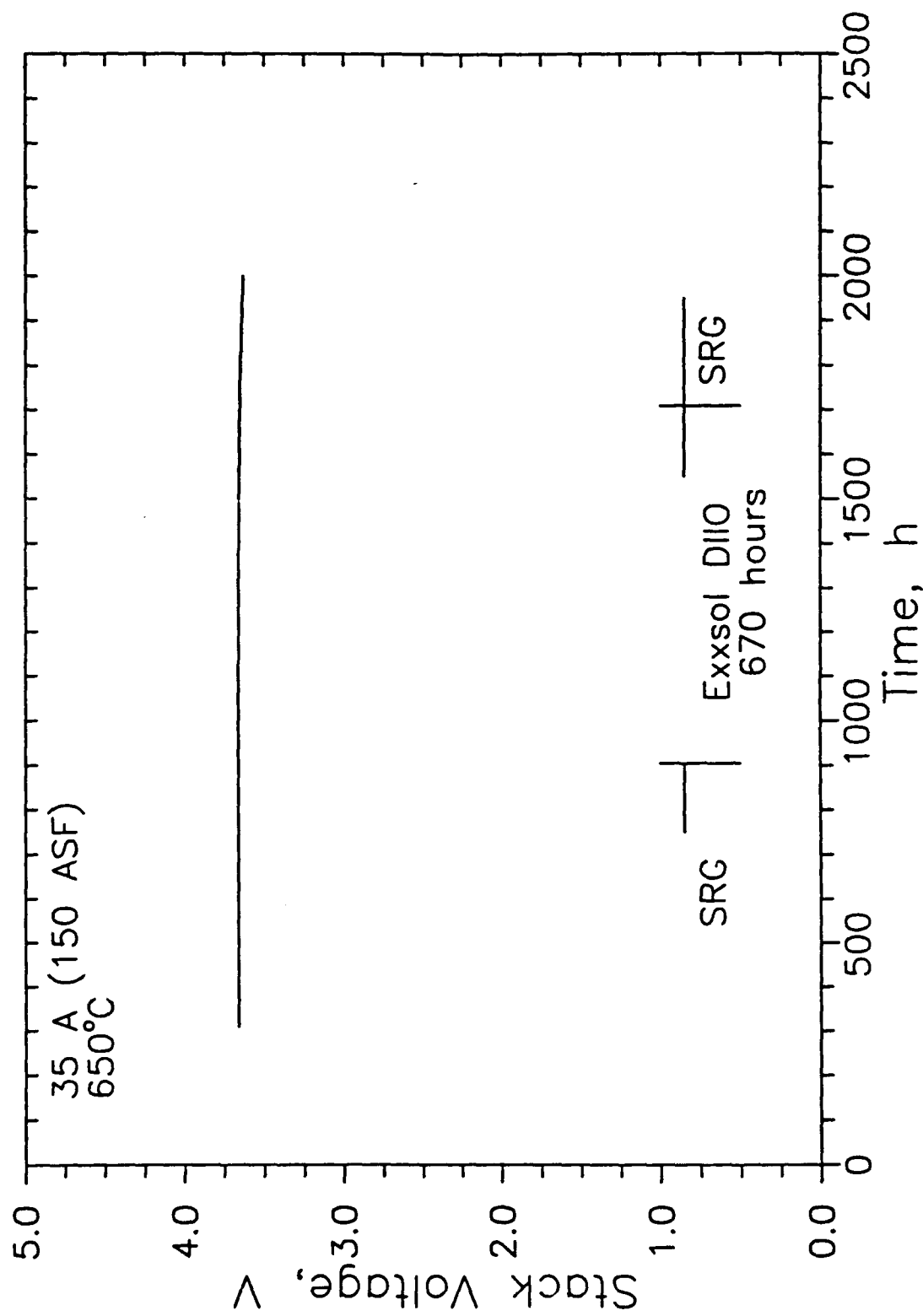
Time, h

remained constant during the demonstration run as may be seen from the composition-time plot presented in Figure 8. This figure also shows a plot of the stack voltage while operating with the EXXSOL D110 fuel.

2.7 Ancillary Tests

As can be seen from the voltage-time plot in Figure 9 the stack output voltage was not affected markedly by switching from SRG to EXXSOL D110. This is, of course, an expected results based on the demonstrated conversion of the fuel to hydrogen in the reforming plate. The reformate composition along with other operating parameters during the test run is presented in Table A-1 in the Appendix.

2.7.1 Carbon Formation

Disassembly of the RU plate showed no evidence of carbon formation. Likewise, teardown inspection of the fuel cell stack showed no carbon either in the fuel manifold or in the cells themselves.

2.8 Conclusions And Recommendations From Tests

The results of this demonstration test shows that Direct Fuel Cell power systems can operate with a low-sulfur, diesel-like fuel. The performance level does not markedly differ from performance with reformed natural gas fuel. Operating with a carbon/steam ratio of 4, an adiabatic preconverter is effective in precluding carbon formation both within the RU and within the cell stack.

Concerning additional testing needed, ERC feels that some development work on the preconverter reactor will be needed to come up with the most effective configuration for adiabatic operation without objectionable carbon deposition rates. Similarly, a better vaporizer design is needed.

Regarding conclusions, ERC also feels that this is a very attractive system and that a demonstration at a 10 kW level should be launched. The weight and volume of the preconverter probably will not be very significant when compared with the rest of the plant. If an external preconverter is needed as it now appears to be the case, its weight will probably contribute less than 5% of the total power plant system weight.

2.8.1 AEL Recommendations

Discussion have continued with Navy technical staff about future scale up of the tests to 10 kW using a Government owned DFC stack. This Phase III effort would also be carried out at ERC using an EPRI owned test setup. Cost sharing has already been obtained from third party agencies for this phase of the scale up work.

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NAVSEA has already agreed to provide sulfur-free diesel fuel for a 400 hour lab test. The remaining issue, as of March 1993, is to provide the funding for this work.

Beyond the 10 kW lab test will be a 60 kW stack for use in "field tests" in about 2 years. Beyond a single 60 kW power plant the power level becomes large enough to drive a small ship. This will be followed by larger ships as the power plant sizes are steadily increased. Fuel cell propulsion for ships will progress at essentially the rate that funding is applied to the initiative. The issue is no longer "whether it will work" it is now "how soon can it be done?"

AEL is eager and willing to proceed. We have also been actively encouraging commercial ship owners to support the work and this business development process continues.

MODULAR DFC POWER

o A "60 KW HALF HEIGHT" STACK - FOR LIQUID FUELS

-- 2 FT X 3 FT, 700 AMPS / CELL, 700 X 0.75 VOLTS = 525 W / CELL

-- 120 CELLS X 0.75 VOLTS / CELL = 90 VOLTS, 525 WATTS X 120 CELLS = 63 KW
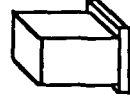
o "ONE SIDED FIT" - MANIFOLDS ON BOTTOM

o BALANCE OF PLANT

-- AIR FILTERS, BLOWERS, HYDROGEN RECOVERY

-- HEAT EXCHANGERS, HEAT RECOVERY DEVICES, EXHAUST

-- FUEL PUMPS, CONTROLS, STARTUP EQUIPMENT, SAFETY EQUIPMENT

o AC INVERTER - OPTIONAL

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3. <u>APPENDICES</u>

APPENDIX 1
SAMPLE DATA SHEET

DATE 7-2-2
TIME 11:10
FUEL oil
LOAD HRS 49.4
SHEET NO 27

31,81.7
3052.3
079.4

OUTPUT

E_tot	5.64
I	35.0
CELL 1	769
CELL 2	762
CELL 3	716
CELL 4	715
CELL 5	679

STACK	
	0.2
	27.5
	58.0
	8.6
	5?

TEMPERATURE °C

STACK 1	646	VAP 5	358
STACK 2	652	VAP 6	308
STACK 3	650 1202	VAP 7	644
STACK 4	647	VAP 8	655
STACK 5	647	PC1	676
STACK 6	634	PC 2	757
STACK 7	612	PC 3	744
STACK 8	610	PC 4	759
STACK 9	646	PC 9 / PC 10 / PC 11	816
		PC 12	820

CH_4		RU 10	
H_2		RU 11	
CO_2		RU 12	
CO		RU 13	
N_2		RU 14	
		RU 15	
		RU 16	

ANALYSIS

	RU	PC
CH_4	31	85
H_2	4.9	50
CO_2	19.5	15.8
CO	8.5	5?
N_2	—	—

NOTES:

FUEL FLOW

H_2O	meter	96	
	g/min	2.95	
Exxsol	meter	62	
	g/min	0.535	

CATHODE FLOW

Air	meter	7039	
	L/min	10.1	
CO_2	meter	98.7ss	
	L/min	3.0	
N_2	meter	57.7g	
	L/min	8.7	

NAVSEA/EPRI LIQUID FUEL DEMONSTRATION THERMOCOUPLE MAP
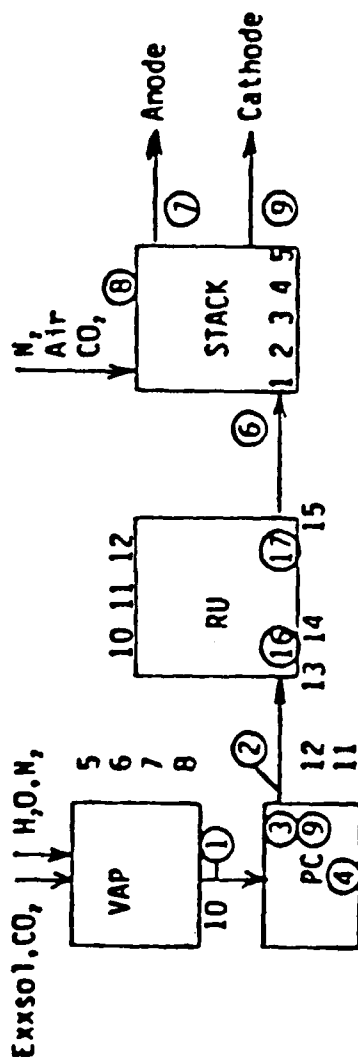
Circled numbers indicate in-stream thermocouple locations, all others are surface locations.

Identification	Function
VAP 5	Heater Temperature
VAP 6	Controller Input
VAP 7	Heater Temperature
VAP 8	Controller Input
PC 1	Vaporizer Outlet
PC 2	PC Outlet
PC 3	PC Upper Bed
PC 4	PC Inlet
PC 9	PC Mid Bed
PC 10	Controller Input
PC 11	Bottom Controller Input
PC 12	Top Controller Input

Identification	Function
RU 10	RU Surface Temperature
RU 11	RU Surface Temperature
RU 12	RU Surface Temperature
RU 13	RU Surface Temperature
RU 14	RU Surface Temperature
RU 15	RU Surface Temperature
RU 16	RU Inlet
RU 17	RU Outlet
STACK 1	Controller Input
STACK 2	Plate Temperature
STACK 3	Plate Temperature
STACK 4	Plate Temperature
STACK 5	Controller Input
STACK 6	Anode Inlet
STACK 7	Anode Outlet
STACK 8	Cathode Inlet
STACK 9	Cathode Outlet

APPENDIX 2

DATA SUMMARY

TABLE A-2
NAVSEA/EPRI LIQUID FUEL DEMONSTRATION DATA SUMMARY

RUN TIME, h	6.1	28.6	49.4	71.7	94	173.2	193.2	214.7	238.6	248.9	267.8	298
TEMP, °F												
Vapor (T_1)	689	693	696	695	695	693	692	689	692	708	708	708
PC Inlet (T_2)	745	733	759	745	738	741	741	739	691	602	660	669
PC Middle (T_2)	803	818	816	819	822	827	825	826	831	863	834	833
PC Outlet (T_2)	749	748	757	752	752	756	753	749	758	744	747	746
RU	1295	1284	1987	1209	1206	1205	1203	1205	1202	205	1207	1208
Stack	1202	1204	1202	1200	1202	1216	1216	1213	1213	1215	1215	1213
FLOW, g/min												
Fuel	0.6	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.51	0.5	0.58	0.5
Water	3.16	2.7	2.95	2.75	3.0	2.75	2.7	2.7	2.75	2.85	3.0	2.8
S/C	4.02	4.13	4.51	4.20	3.82	4.20	4.13	4.13	4.12	4.35	3.95	4.28
ANALYSIS, Vol%												
PC Outlet												
CH_4		23.8	18.9	21.4	21.6	21.7	18.7	21.6		30.2	31.1	30.6
H_2		45.7	50.0	48.3	48.0	49.5	51.4	49.4		44.7	43.8	44.3
CO_2		28.9	15.9	27.2	25.4	27.8	26.2	23.4		20.4	24.5	24.6
CO		0.71	0.95	0.6	0.62	0.66	1.85	0.89		0.6	0.6	0.61
RU Outlet												
CH_4	4.1	1.8	3.1	5.3		1.5	0.72		1.65	0.6		1.3
H_2	61.2	69.7	66.9	64.0		69.6	67.7		70.9	71.0		73.0
CO_2	19.7	18.1	19.5	21.4		18.5	16.8		18.2	18.1		18.6
CO	14.4	10.3	8.5	7.3		10.3	10.5		10.1	10.2		10.1
STACK, Volts	3.68	3.68	3.64	3.63	3.63	3.68	3.69	3.66	3.67	3.68	3.67	3.67
Current, Amperes	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0

TABLE A-2 (cont.)
NAVSEA/EPRI LIQUID FUEL DEMONSTRATION DATA SUMMARY

RUN TIME, h	387.5	411.7	441.4	460	484.7	558	632.7
TEMP. °F							
Vapor (T_1)	707	714	711	707	716	705	712
PC Inlet (T_4)	677	679	680	680	681	682	684
PC Middle (T_2)	830	828	827	826	822	823	821
PC Outlet (T_2)	744	751	749	745	746	746	749
RU	1213	1209	1208	1205	1207	1207	1708
Stack	1206	1215	1215	1213	1215	1215	1216
FLOW, g/min							
Fuel	0.5	0.5	0.49	0.54	0.5	0.5	0.5
Water	2.72	3.0	2.73	2.70	2.7	3.0	3.0
S/C	4.16	4.58	4.26	3.82	4.13	4.58	4.58
ANALYSIS, Vol%							
PC Outlet							
CH_4	31.5	29.2	32.1	31.9	32.8		30.80
H_2	43.0	45.2	39.7	39.4	39.0		43.39
CO_2	24.6	24.6	24.6	24.7	24.6		25.15
CO	0.6	0.64	0.45	0.41	0.39		0.66
RU Outlet							
CH_4	0.73	0.58		0.63	0.63		
H_2	72.5	73.4		69.9	68.3		
CO_2	17.9	18.2		17.9	17.7		
CO	11.0	10.6		10.9	10.9		
STACK, Volts	3.63	3.65	3.65	3.63	3.64		
Current, Amperes	35.0	35.0	35.0	35.0	35.0	35.0	35.0

APPENDIX 3

DFC ENERGY BALANCE

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A.3   DFC ENERGY BALANCE

Utilizing ERC's computer codes, an overall system mass and energy balance was prepared and is shown on the following pages.   The balance was based on a 234-cell, 0.327 square meter active cell area stack. The key parameters for this stack operating with preconverted fuel are:

Power output, kW	80.4
Fuel utilization in anode, %	75.0
Oxygen utilization in cathode, %	47
Cell potential, mV	752
Stack current, A	457
Stack temperature, ^{O}F	1275

Since ERC does not have a computer code for a DFC system operating with diesel type fuel (DF), ERC estimated the heat load vaporization and superheat (ΔH_V = 150 Btu/lb, Cp = 0.6 Btu/lb/F^{O}). This heat requirement produces a temperature drop of about 200°F in the steam flowing from the boiler to the preconverter.

The fuel cell anode inlet temperature was increased by exchanging heat with the cathode exhaust.   This change was incorporated in the computer model.

As a result of accounting for these thermal loads, the temperature of the exhaust from the system calculated using the modified code was reduced from 560°F to 395°F. This is still a viable exit temperature for the system. If desired, the temperature may be elevated by increasing the rate of flow of the DF. For example, increasing the flow from 28 lb/h to 30 lb/hr will increase exhaust temperature to 474°F.

A summary of the revised node analysis is attached along with a simplified system diagram showing key streams and temperatures.
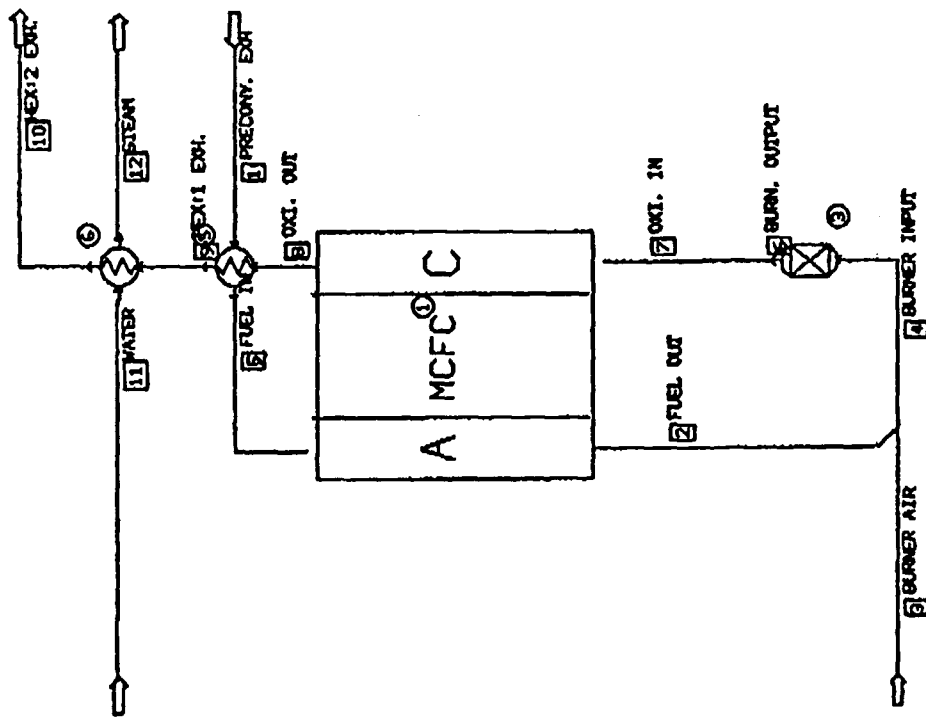
70 kW CTC POWER PLANT M & E BALANCE (With Fuel Preheater)

Project: DOE	
Title: MATERIAL BALANCE	
Date: 12/14/92	
Checked:	
Approved:	
Drawing No:	Rev:

Preconv.: Diesel Fuel, 75% Fuel Util.

For DF (2·lb/h)

$\Delta H_v = 150\ BTU/lb$ (est.)

$\rho_f = 0.6\ BTU/lb$ (est.)

$70°F(l) \rightarrow 750F(g)$: $536\ BTU/lb$

$530 \times \dfrac{13.8}{72} \times \dfrac{1}{0.5} = \sim200\ F\ \Delta T\ steam$

Stream ID	1	2	3	5	7	8	10	11	12
Stream label	PRECONV. EXH	FUEL OUT	BURNER AIR	FUEL IN	OXI. IN	OXI. OUT	HEX12 EXH.	WATER	STEAM
Flow rate (lbmol/hr)	9.406	16.33	25.62	9.406	41.22	34.62	34.62	8.091	8.091
Temperature (deg F)	700	1275	70	1100	1100	1275	395.1	70	900
Enthalpy (K BTU)	137.4	334.9	224.3	174.4	714.5	640.5	393	-78.9	131.6
-- Component Flow Rates (lbmol/hr) --									
Hydrogen	0.8091	0.9938	0	0.8091	0	0	0	0	0
Methane	1.264	1.881e-005	0	1.264	0	0	0	0	0
Ethane	0	0	0	0	0	0	0	0	0
Carbon Monoxide	0	0.4727	0	0	0	0	0	0	0
Carbon Dioxide	0.7586	5.95	0	0.7586	6.423	2.023	2.023	0	0
Water	6.574	8.918	0	6.574	9.912	9.912	9.912	8.091	8.091
Nitrogen	0	0	20.24	0	20.24	20.24	20.24	0	0
Oxygen	0	0	5.382	0	4.649	2.449	2.449	0	0

70 kW DFC POWER PLANT M & E BALANCE
(With Fuel Preheater)

Project:	DOE		
Date: 12/14/92	Checked:	Approved:	Rev:
Title: MATERIAL BALANCE		Drawing No:	

Presurized Diesel Fuel, 70w Fuel Util.

Stream ID	1	2	3	5	7	8	10	11	12
Stream label	PRECONV. EXH	FUEL OUT	BURNER AIR	FUEL IN	OXI. IN	OXI. OUT	HEX12 EXH.	WATER	STEAM
Flow rate (lbmol/hr)	10.08	17.19	30.94	10.08	47.19	40.59	40.59	8.091	8.091
Temperature (deg F)	700	1236	70	1100	1100	1236	473.9	70	900
Enthalpy (K BTU)	147.2	343.7	270.9	186.8	813.3	734.3	484.1	-78.9	131.6
-- Component Flow Rates (lbmol/hr) --									
Hydrogen	0.8669	1.331	0	0.8669	0	0	0	0	0
Methane	1.355	8.739e-005	0	1.355	0	0	0	0	0
Ethane	0	0	0	0	0	0	0	0	0
Carbon Monoxide	0	0.5548	0	0	0	0	0	0	0
Carbon Dioxide	0.8128	6.012	0	0.8128	6.567	2.167	2.167	0	0
Water	7.044	9.29	0	7.044	10.62	10.62	10.62	8.091	8.091
Nitrogen	0	0	24.44	0	24.44	24.44	24.44	0	0
Oxygen	0	0	6.499	0	5.556	3.356	3.356	0	0
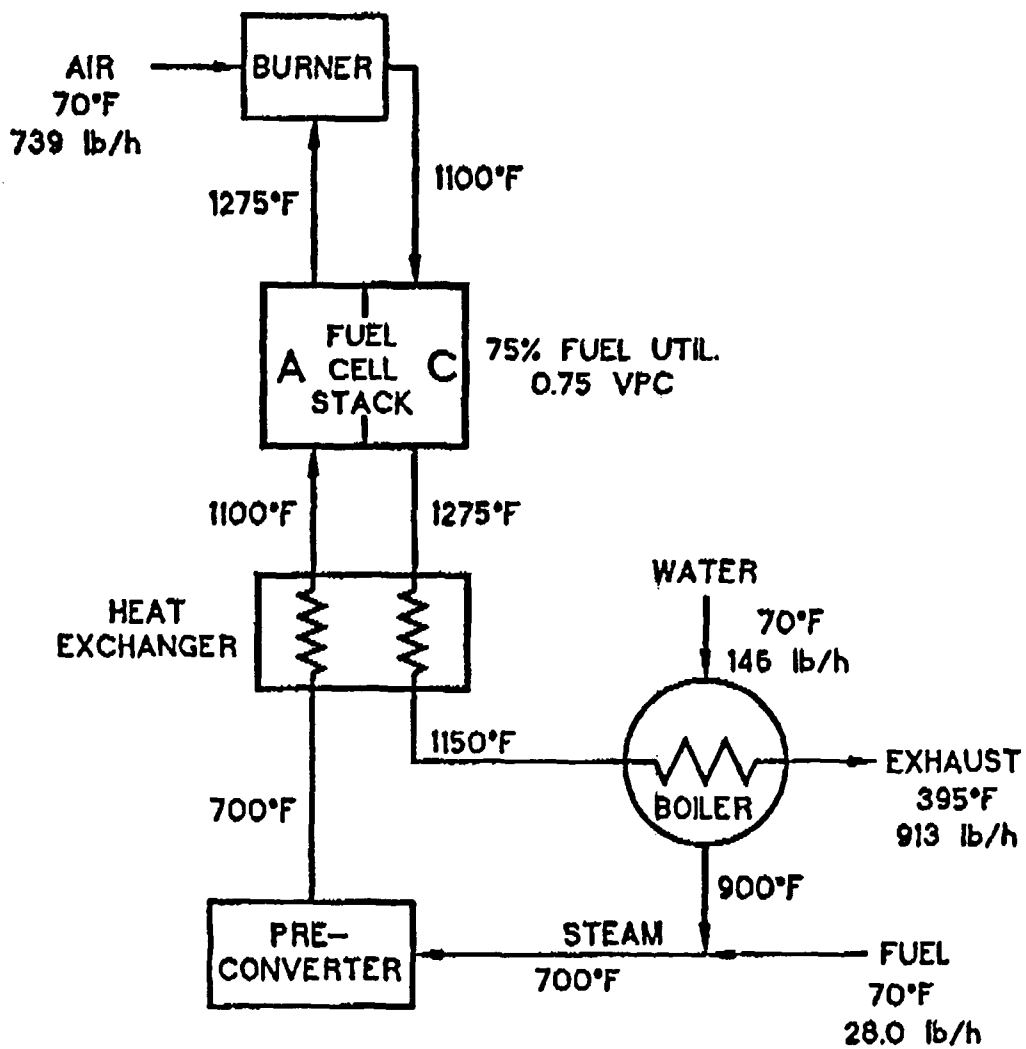
SD1252

APPENDIX 4

PRECONVERTER THERMAL BALANCE

A.4 THERMAL BALANCE FOR PC

Preconversion of liquid fuels to methane and hydrogen is needed to prevent coking in the reforming plates of the fuel cell stack. In order to retain the simplicity and high efficiency of the DFC system, the preconverter (PC) unit should be operating at essentially thermoneutral process conditions. An adiabatic PC reactor requiring no thermal management can then be employed in the DFC system between the vaporizer and the fuel cell stack.

The product gas composition at the thermoneutral operating point for the reactor can be readily estimated by utilizing a heat of combustion balance for the reactants and products. The following values were used for the net heats of combustion:

Diesel Oil $(CH_{1.8})_n$	258,000 Btu/mol/n
Methane (CH_4)	346,000 Btu/mol
Hydrogen (H_2)	104,000 Btu/mol

The heat balance for the reaction

$$CH_{1.8} + nH_2O \longrightarrow (1-0.5n)CH_4 + (2n-1.1)H_2 + 0.5nCO_2$$
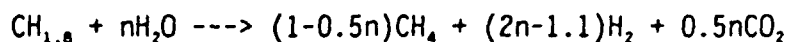
shows that the reaction is slightly endothermic when $n = 0.8$ and slightly exothermic when $n = 0.7$, as seen from the product heat values tabulated in Table A.4-1. (Because CO concentration is less than 0.6%, its effect on the thermal balance is small.) The preconverted fuel gas flowing to the stack will, therefore, have a methane content of 40-50% on a dry basis.

TABLE A.4-1

PRECONVERTER HEAT BALANCE

Basis: 1 lbmol of $CH_{1.8}$ (13.8 lb, 18,700 Btu/lb)

$$CH_{1.8} + nH_2O \longrightarrow (1-0.5n)CH_4 + (n-1.1)H_2 + 0.5nCO_2$$
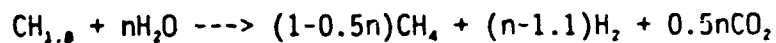
	n = 0.8	0.75	0.7
Methane			
mols	0.6	0.625	0.65
Btu	207,600	216,250	224,900
Vol %	40.0	44.6	50.0
Hydrogen			
mols	0.5	0.4	0.3
Btu	52,000	41,600	31,200
Vol %	33.3	28.6	23.1
CO_2			
mols	0.4	0.375	0.35
Vol %	26.7	26.8	26.9
Total			
mols	1.5	1.4	1.3
Btu	259,600	257,850	256,100
Balance, Btu	-1,600	+150	+1,900